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Tactile Sensing and Information Processing for Man and Machine Systems

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1. Scientific Progress Overview

The project on Tactile Sensing and Information Processing for Man and Machine Systems is completing its fifth year. Accomplishments include the continued development of tactile sensors and algorithms for sensor-based exploration and control, and continued development of models of human mechanoreception in manipulation.

In the area of sensor development, researchers at Stanford have investigated stylus sensors for surface exploration. Tests were conducted with NASA Ames (see Technology Transitions) to evaluate the stylus as a tool for remote geological exploration. Very high resolution tactile arrays have also been fabricated and tested. The arrays are CMOS-compatible and contain circuitry for scanning or individually accessing the elements. Sensitivities are approximately 51 mV/kPa for normal stresses and 12 mV/kPa for shear stresses. An improved optical sensor has been developed for measuring local object geometries been developed and applied to the design of a medical probe.

In the area of control and sensor based exploration, robot fingers have been used to manipulate objects of unknown shape while simultaneously collecting information about the objects' geometric features

In the area of human/machine interaction, experiments were conducted to determine the ability of subjects to distinguish fine features on real and virtual surfaces and to accurately detect contacts with virtual objects using ungrounded haptic feedback.

2. Significant Accomplishments

Stanford University

Comparison of Grounded and Ungrounded Haptic Interfaces

a) Description

Haptic interfaces, that apply forces to the fingertips of a human operator, can be classified as grounded or ungrounded. Grounded devices, such as SensAble Devices' Phantom or Immersion's Impulse Engine, are attached to a stationary object such as a desk. When the operator touches a virtual wall, a contact force is applied through the interface, inhibiting further motion. For ungrounded devices a contact force is felt but there is no impediment to motion of the arm. Little prior research has been done on the perceptual effects of displaying contacts with virtual objects using an ungrounded haptic interface. Experiments were conducted at Stanford to compare how accurately subjects could identify contacts with virtual walls using ungrounded versus grounded feedback. Two haptic interfaces were constructed and operated in three modes: with grounded force feedback applied to the wrist, with ungrounded forces applied to the fingertips, and with grounded wrist forces in addition to fingertip forces. Tests were conducted to see how quickly subjects could arrest motion upon sensing contact (measured as virtual boundary penetration) and how accurately they could distinguish among objects of different size (see figure 1) [Richard and Cutkosky 1997].

Although the grounded feedback unsurprisingly resulted in smaller boundary penetrations, the results and subjects' comments showed that ungrounded force feedback was effective at rendering virtual object surfaces. With ungrounded feedback subjects had no difficulty in distinguishing among objects with a difference in size of 0.5 cm and greater. The size discrimination experiments were subsequently repeated using a prototype device from Virtual Technologies Corp. (see figure 2), used to teleoperate a two-fingered robot hand. Despite the compliance present in the ungrounded Cybergrasp prototype, subjects were again able to distinguish among objects whose dimensions differed by 0.5 cm or greater.

b) Significance

Ungrounded haptic interfaces, which can be worn on the arms and wrists, are attractive for virtual reality applications because they can be made minimally encumbering as compared to stationary, grounded devices. However, the ability of ungrounded devices to effectively display contact forces with virtual objects has been a subject of concern. The experiments conducted at Stanford reveal that while grounded force feedback is unsurprisingly better at reducing artificial effects such as the penetration of virtual object surfaces, ungrounded force feedback is nonetheless effective for displaying contacts. The effectiveness of ungrounded feedback is improved when visual feedback, and cutaneous feedback consisting of contact forces applied at the fingertips, are part of the package. However, it is essential that time delays associated with these different channels be equalized.

c) Figures

Figure 1. A comparison of grounded versus ungrounded haptic feedback. How effective is ungrounded feedback for displaying contacts with virtual objects?

Figure 2. Example of ungrounded haptic feedback being used for teleoperation of a two-fingered robot hand. The device is a prototype of Cybergrasp, developed at Virtual Technologies Inc. by Dr. Marc Tremblay, an alumnus of the ONR project on Tactile Sensing and Information Processing for Man and Machine Systems.

Figure 3. Boundary discrimination tests with different modes of haptic feedback: (A) ungrounded fingertip forces, (B) grounded feedback applied to the wrist, (C) grounded wrist feedback + fingertip forces. Although grounded feedback worked best for objects of very similar size, subjects had little difficulty with differences of 0.5 cm or greater using ungrounded feedback [Richard and Cutkosky 1997].

Harvard University

Image-Based Tactile Sensing

a) Description

During the past year, we have developed and implemented the design of a novel image-based tactile sensor. Besides being able to localize contact position, this sensor can recover information about contact shape as well. Unlike the majority of existing haptic technologies, this sensor uses vision-based methodologies. The original design for the sensor (see figure 4(a) in the Appendix) used a ccd camera, pinhole, and led lighting. The current design (see figure 4(b) in the Appendix) uses a more robust microcamera with lens and fiber optic lighting.

The operation of the sensor is based on using the camera to image the inside surface of the sensor membrane tip. The membrane is filled with clear liquid-like silicon RTV and sealed from the electronics by a clear window. A pattern of dots is drawn on the inner surface of the membrane. As an object makes contact and deforms the sensor membrane, the pattern of dots deforms as well. Using the mechanics of the membrane as well as constant volume and minimum energy requirements for the deformed membrane surface, our algorithm computes the shape of the tactile surface as it is being deformed. A typical example of a pattern seen by the sensor camera together with the reconstructed 3-D membrane surface are given in figure 5 (in the Appendix.) Our current software implementation allows us to reconstruct the sensor surface at a rate of 7Hz, a significant increase from the speed of 1Hz obtained a year ago.

b) Significance

Dexterous robots have been widely studied and developed over the past decade for use in dexterous manipulation of objects in automated, remote, or hostile environments. Tactile sensing is essential for such robots, much as it is for humans performing dexterous tasks. In the past, tactile surfaces for dexterous robotic hands have been modeled as rigid partly due to a lack of deformable tactile sensors and partly to simplify computations. However, manipulating rigid objects with rigid fingertips is neither robust nor realistic. Our image-based tactile sensor behaves much like a human fingertip in that it is both deformable and capable of localizing contact in three dimensions. Used as a fingertip at the end of robotic fingers (see figure 3), the sensor provides essential haptic information and vastly improves the grasp stability and robustness.

c) Figures (see Appendix)

3. Productivity Report

(a) papers published in refereed journals

A. Z. Hajian and R. D. Howe, "Identification of the mechanical impedance at the human finger tip," *ASME Journal of Biomechanical Engineering*, v 119 n 1 Feb 1997. pp 109-114..

B.J. Kane, M.R. Cutkosky and G.T.A. Kovacs, "CMOS-compatible traction stress sensor for use in high-resolution tactile imaging," *Sensors and Actuators*, v. A 54, n. 1-3, June 1996, pp. 511-516.

R.D. Howe and M.R. Cutkosky, "Practical Force-Motion Models for Sliding Manipulation," The International Journal of Robotics Research, v. 15, n. 6, December 1996, pp. 557 –572.

J.S. Son, M.R. Cutkosky and R.D. Howe, "Comparison of Contact Sensor Localization Abilities During Manipulation," *Robotics and Autonomous Systems*, v. 17, n. 3, June 1996, pp. 217-233.

I. Kao, M.R. Cutkosky, B. Edin, G. Westling and R. Johansson, "Robotic Stiffness Control and Calibration as Applied to Human Grasping Tasks," *IEEE Transactions on Robotics and Automation*, v. 12, n. 4, August, 1997, pp.557-566.

(b) papers accepted for publication in refereed journals

A. Z. Hajian, D. S. Sanchez, and R. D. Howe, "Drum roll: Increasing bandwidth through passive impedance modulation," accepted for publication in the IEEE Transactions on Robotics and Automation, 1997.

W. J. Peine, K. C. Foucher, and R. D. Howe, "Finger speed during single digit palpation," accepted for publication in Human Factors,1997.

D. T. V. Pawluk, J. S. Son, P. S. Wellman, W. J. Peine, and R. D. Howe., "A Distributed Pressure Sensor For Biomechanical Measurements," ASME Journal of Biomechanical Engineering, in press, 1997.

(c) technical reports and conference articles

C. Richard and M.R. Cutkosky, "Contact Force Perception with an Ungrounded Haptic Interface", 1997 ASME IMECE 6th Annual Symposium on Haptic Interfaces, Dallas, TX, Nov. 15-21.

A. West and M.R. Cutkosky, "Detection of Real and Virtual Fine Surface Features with a Haptic Interface and Stylus," 1997 ASME IMECE 6th Annual Symposium on Haptic Interfaces, Dallas, TX, Nov. 15-21.

C. Richard, A.M. Okamura, M.R. Cutkosky, "Getting a Feel for Dynamics: using haptic interface kits for teaching dynamics and controls," 1997 ASME IMECE 6th Annual Symposium on Haptic Interfaces, Dallas, TX, Nov. 15-21.

A.M. Okamura, M.L Turner and M.R. Cutkosky, "Haptic Exploration of Objects with Rolling and Sliding," Proceedings of the 1997 IEEE International Conference on Robotics and Automation, Vol. 3, April 20-25, Albuquerque, NM, pp. 2485-2490.

N. J. Ferrier, K. A. Morgansen, D. Hristu. "Implementation of Membrane Shape Reconstruction." Tech. Report 97-1, Harvard Robotics Lab, Harvard University, 1997.

W.J. Peine, P.S. Wellman and R. D. Howe, "Temporal bandwidth requirements for tactile shape displays," to be presented at the Sixth Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, ASME International Mechanical Engineering Congress and Exposition, Dallas, Nov. 15-21, 1997.

J.T. Dennerlein, P. Millman, and R.D. Howe, "Vibrotactile Feedback for Industrial Telemanipulators," to be presented at the Sixth Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, ASME International Mechanical Engineering Congress and Exposition, Dallas, Nov. 15-21, 1997.

A. Z. Hajian, D. S. Sanchez, and R. D. Howe, "Drum roll: Increasing bandwidth through impedance modulation," presented at the IEEE International Conference on Robotics and Automation, Albuquerque, New Mexico, April 20 - 25, 1997.

P. E. Dupont, T. M. Schulteis, and R. D. Howe , "Experimental Identification of Kinematic Constraints," presented at the IEEE International Conference on Robotics and Automation, Albuquerque, New Mexico, April 20 - 25, 1997.

D. T.V. Pawluk and R. D. Howe, "Contact pressure distribution on the human finger pad," presented at the 26th Congress of the International Society of Biomechanics, Tokyo, August 25-29, 1997.

D. T.V. Pawluk and R. D. Howe, "Mechanical impedance and energy dissipation in the human finger pad," 1997 ASME Summer Bioengineering Conference, Sun River, Oregon, June 1997, BED-Vol. 35, p. 591-592.

P.S. Wellman, W.J. Peine, G. Favalora, and R.D. Howe, "Mechanical Design and Control of a High-Bandwidth Shape Memory Alloy Tactile Display," Fifth International Symposium on Experimental Robotics, Barcelona, June 16-18, 1997, Springer-Verlag (in press).

(d) books or book chapters

(e) books or book chapters in press

(f) patents filed or granted

(g) invited presentations

D. Hristu, D. A. Kontarinis, and R.D. Howe,
6/30/96
International Federation of Automatic Controls World Congress
San Francisco, CA
Title: A comparison of delay and bandwidth limitations in teleoperation

R. Brockett
10/12/96
4th International Conference on Hybrid Systems
Ithaca NY
Title: Learning Boolean Expressions via Principal Components

R. Brockett
11/14/96
University of British Columbia
Vancouver, BC, Canada
Title: Modeling Intelligent Systems: Languages, Automata, and Differential Equations

R. Brockett
11/19/96
Brown University
Providence, RI
Title: Performance Enhancement Through Optimal Allocation of Effort

R. Brockett
3/2/97
Joint Conference on Information Systems
Duke University
Durham, NC
Title: Near Optimal Control with Communications Constraints

R. Brockett
3/23/97
GAMM 97
University of Regensburg
Regensburg, Germany
Title: Mathematical Approaches to Learning Applied to Control Systems

R. Brockett
4/8/97
ASYNC 97
Eindhoven University of Technology
Eindhoven, the Netherlands
Title: Methods of Analysis for Asynchronous Systems

R. Brockett
5/29/97
Morningside Center of Mathematics
Chinese Academy of Sciences
Beijing, China
Title: Lectures of Nonlinear Control Systems

(h) contributed presentations

(i) transitions of ideas to industry or military

On November 12, 1996, Stanford graduate student M. Costa collaborated with researchers at the NASA Ames Intelligent Mechanisms Group (IMG) to conduct a field test of a stylus (fingernail) sensor developed at Stanford. The test was conducted on the Marskohod rover at a remote site in the Arizona desert. The stylus was attached to an end-effector on the rover and used to scratch the surfaces of rocks. Data collected by the stylus were sent via satellite to Mountain View, CA where they were displayed to geologists through a haptic interface. The experiment demonstrated the potential utility of haptic feedback as an adjunct to other sensory channels (e.g., video) for remote field geology.

In August 1997, the Stanford Dextrous Manipulation Lab became a subcontractor to Virtual Technologies Inc. of Palo Alto, CA, under ONR STTR Topic Number N96T003: "A Grasp and Arm Force Feedback System." In this project, Virtual Technology's CyberGlove is equipped with a prototype force feedback apparatus and used to control a two-fingered manipulator in the Dextrous Manipulation Lab. The goal of the joint experiments is to quantify the efficacy of "ungrounded" finger force feedback, and to develop teleoperation methods that map between a gloved human hand manipulating virtual objects and a robot hand manipulating real objects.

In June 1997, Stanford's Dextrous Manipulation Laboratory entered into a contract with Interval Research corporation of Palo Alto, CA to investigate the tactile and kinesthetic properties of devices, such as miniature mechanisms, for which the dynamics are dominated by friction. The project involves the design of a haptic interface that will be used to identify the dynamic properties of devices, including a model of the friction, and to render the models of such devices to human subjects.

In August 1997, the Stanford Dextrous Manipulation Lab became a subcontractor to Immersion Inc., San Jose CA, under an STTR project on an "Advanced Reconfigurable Haptic Interface System." The goal of this project is to develop methods for efficiently identifying and representing the surface properties of objects in a remote or virtual environment. The work will include the development of exploratory procedures, and the development of data representations suitable for describing objects with texture and fine features.

The Harvard Robotics Lab's image-based surface reconstruction technology has lead to the development of an endoscopic probe for use in minimally invasive surgery. This is in cooperation with the Harvard Center for Minimally Invasive Surgery at Deaconess Hospital, headed by Dr. Armour Forse.

Harvard University and Immersion Corporation have collaborated on a Phase I STTR (ONR contract N00014-96-C-0325), entitled "Commercialization of Vibrotactile Feedback for Telemanipulation and Virtual Environments." This project involves collecting vibration data

resulting from using a stylus to tap, scratch, and puncture, various materials, textures, and membranes. Empirical models were fit to these data to create a library of waveforms. Preliminary results of this integration indicate that vibration feedback enhanced operator performance for several different tasks. An STTR Phase II proposal to realize commercial prototype systems using vibrotactile feedback has been submitted.

(j) training data

Stanford:

Undergraduates: 0
Graduate students: 5 (1 woman, 0 non-US citizen, 3 minority)
Post Docs: 0

Harvard:

Undergraduate Students: 8
Graduate Students: 4 (1 Woman, 1 non-US citizen)
Post-docs: 2 (1 non-US citizen)

(k) awards and honors

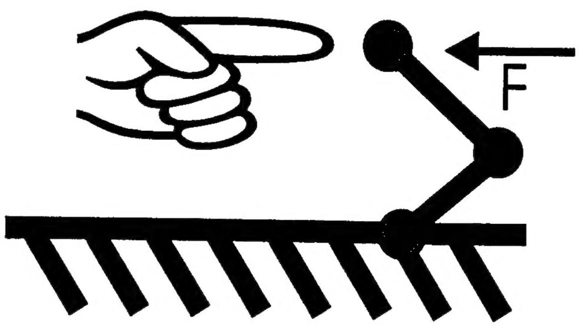
(l) cost and descriptions of items exceeding $1000

Stanford:
IBM-compatible computer system for haptic interface programming: $3500
Immersion Inc. Impulse Engine haptic interfaces and associated software: $5000

Harvard:
ELMO QN401 Microcamera: $3264
EPIX 4MIP Image Processing and Acquisition Board: $5081

Grounded vs. Ungrounded Haptic Feedback

Grounded



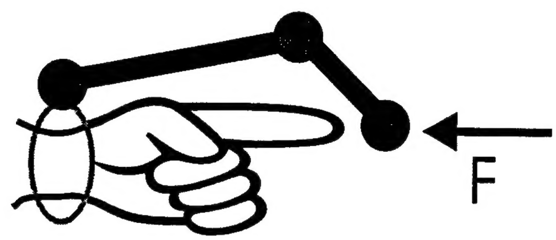
Forces applied with respect to a stationary reference frame

Examples:
PHANToM, Impulse Engine

Absolute force reference
Accurate rendering of stationary objects

Limited Workspace

Ungrounded



Forces applied locally with respect to arm or hand

Examples:
Cybergrasp, Rutgers Master II

Large Workspace
Portable

Cannot impede arm motion

Question: How effectively can ungrounded devices display contact with stationary objects?

Figure 1.

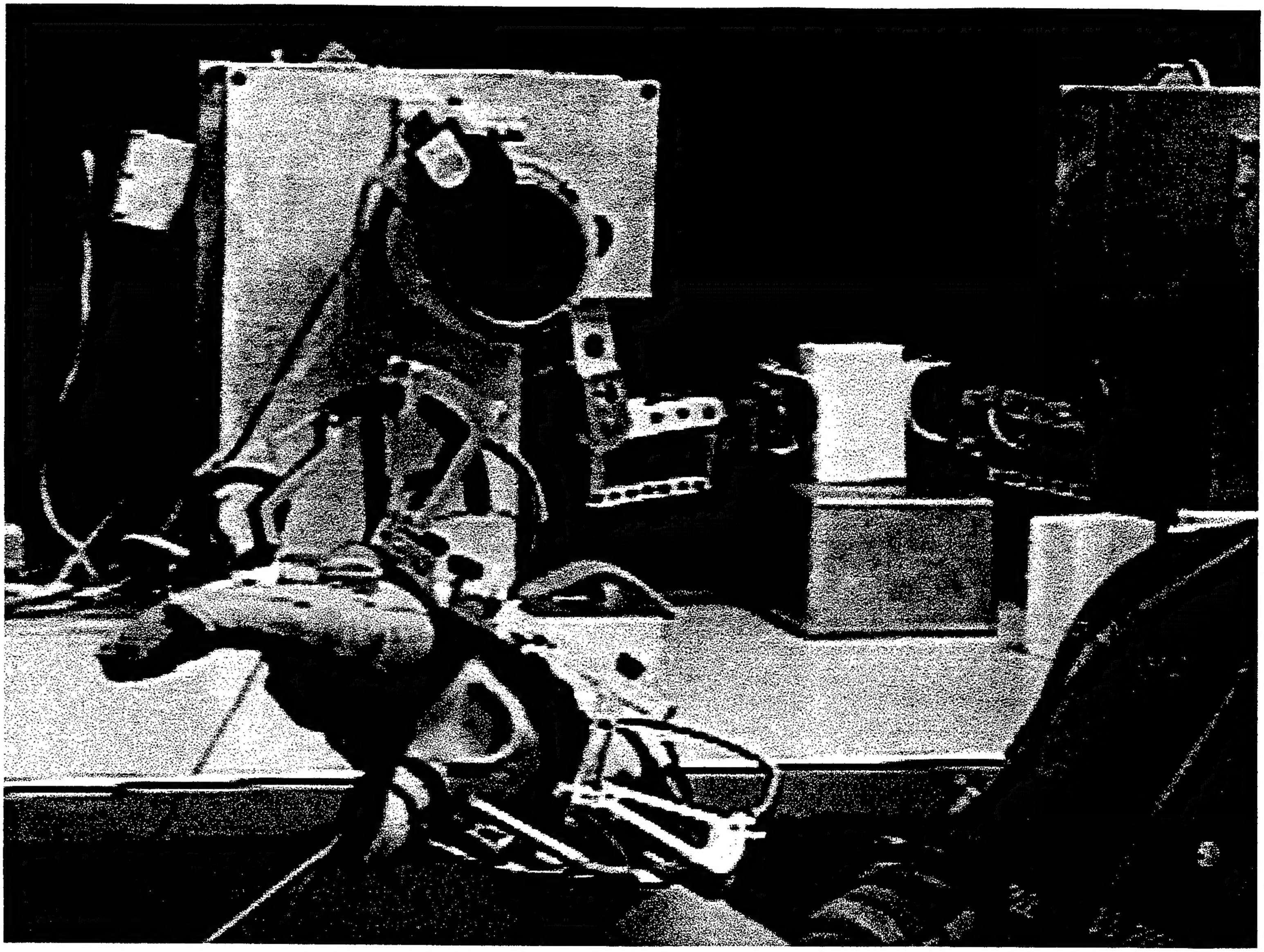


Figure 2. Example of ungrounded feedback: Using Cybergrasp from Virtual Technologies Inc. to tele-operate a dextrous manipulator.

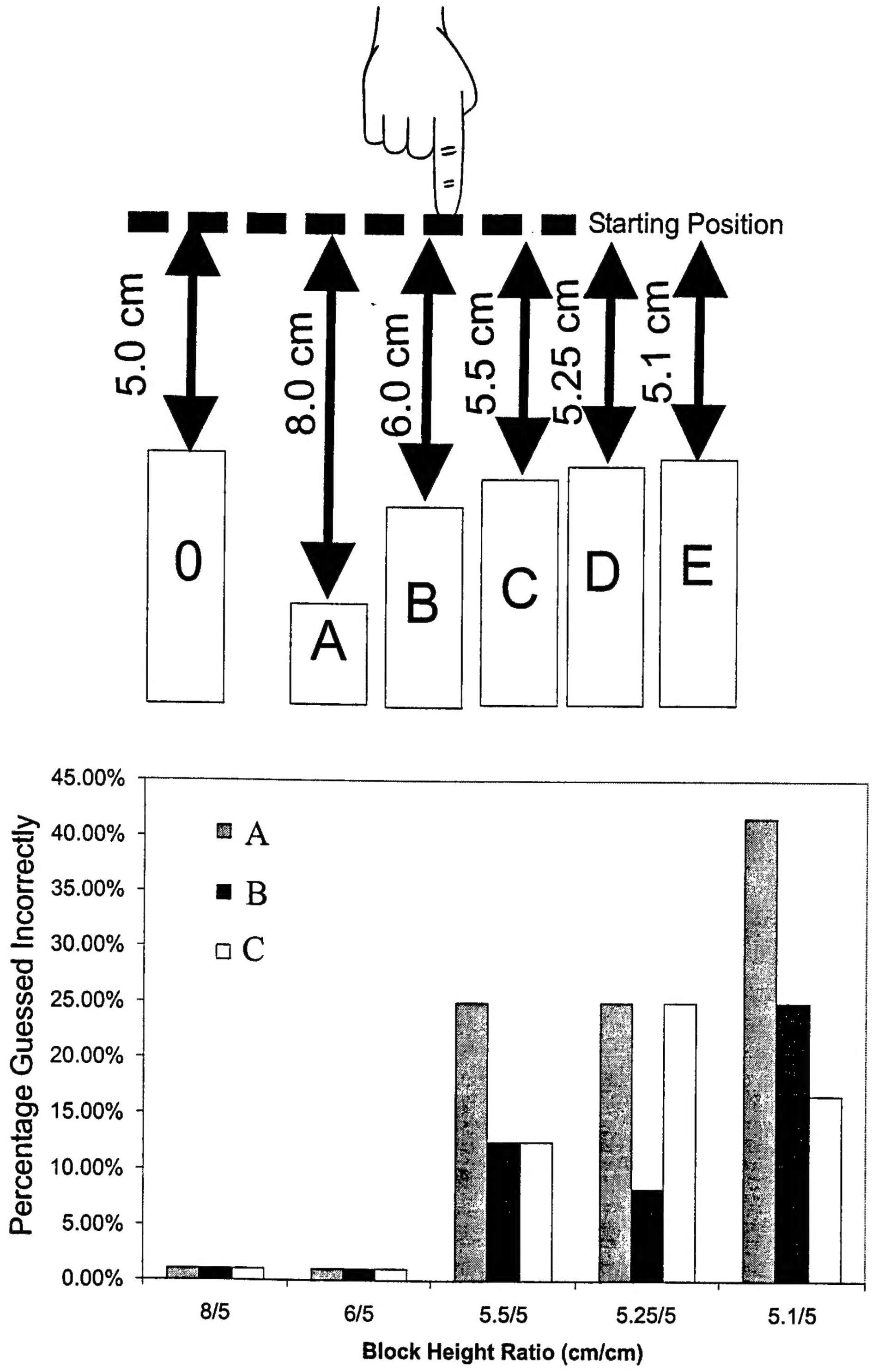


Figure 3. Typical results from [Richard and Cutkosky, 1997] for object discrimination with three types of feedback: A) ungrounded B) grounded c) grounded with fingertip forces.

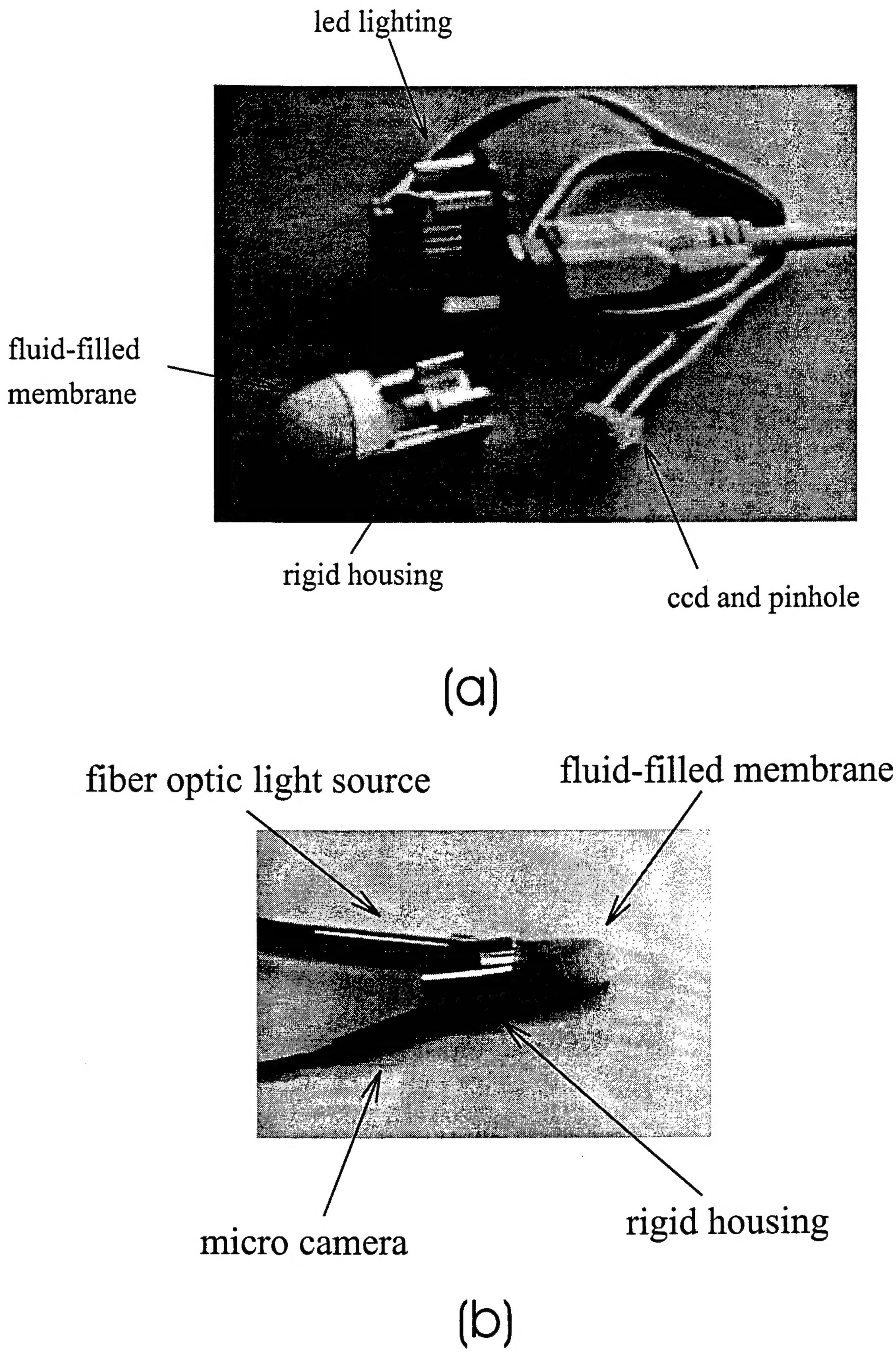

led lighting
fluid-filled membrane
rigid housing
ccd and pinhole
(a)
fiber optic light source
fluid-filled membrane
micro camera
rigid housing
(b)

Figure 4.

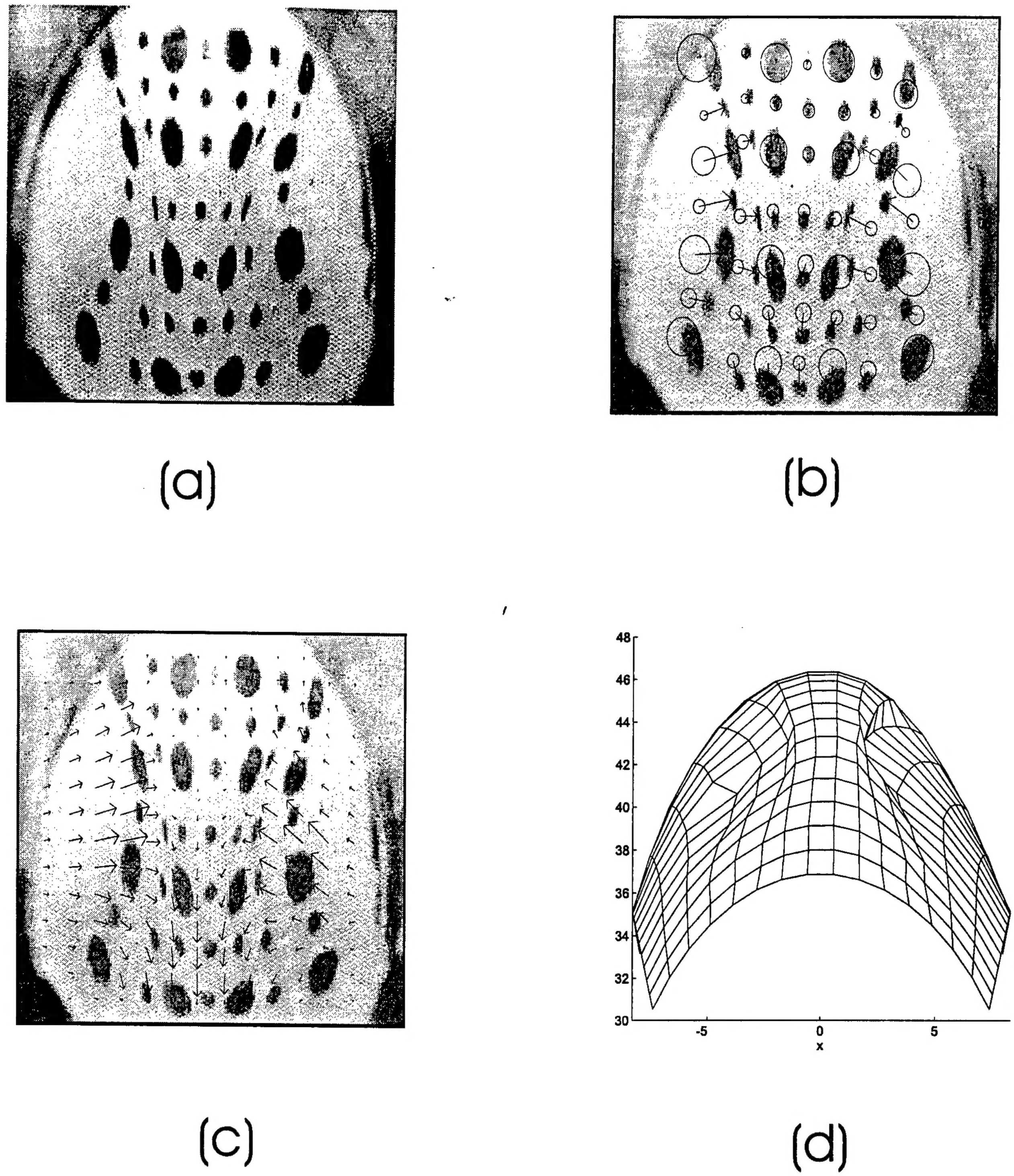


Figure 5.